Ministry of Natural Resources

21

CLIMATE CHANGE RESEARCH REPORT CCRR-21

Responding to Climate Change Through Partnership

Potential Effects of Climate Change and Adaptive Strategies for Lake Simcoe and the Wetlands and Streams Within the Watershed

Ontario

Sustainability in a Changing Climate: An Overview of MNR's Climate Change Strategy (2011-2014)

Climate change will affect all MNR programs and the natural resources for which it has responsibility. This strategy confirms MNR's commitment to the Ontario government's climate change initiatives such as the Go Green Action Plan on Climate Change and outlines research and management program priorities for the 2011-2014 period.

Theme 1: Understand Climate Change
MNR will gather, manage, and share information and knowledge about how ecosystem composition, structure and function – and the people who live and work in them – will be affected by a changing climate. Strategies:

- Communicate internally and externally to build awareness of the known and potential impacts of climate change and mitigation and adaptation options available to Ontarians.
- Monitor and assess ecosystem and resource conditions to manage for climate change in collaboration with other agencies and organizations.
- Undertake and support research designed to improve understanding of climate change, including improved temperature and precipitation projections, ecosystem vulnerability assessments, and improved models of the carbon budget and ecosystem processes in the managed forest, the settled landscapes of southern Ontario, and the forests and wetlands of the Far North.
- Transfer science and understanding to decision-makers to enhance comprehensive planning and management in a rapidly changing climate.

Theme 2: Mitigate Climate Change
MNR will reduce greenhouse gas emissions in support of Ontario's greenhouse gas emission reduction goals. Strategies:

- Continue to reduce emissions from MNR operations though vehicle fleet renewal, converting to other high fuel efficiency/low-emissions equipment, demonstrating leadership in energy-efficient facility development, promoting green building materials and fostering a green organizational culture.
- Facilitate the development of renewable energy by collaborating with other Ministries to promote the value of Ontario's resources as potential green energy sources, making Crown land available for renewable energy development, and working with proponents to ensure that renewable energy developments are consistent with approval requirements and that other Ministry priorities are considered.
- Provide leadership and support to resource users and industries to reduce carbon emissions and increase carbon storage by undertaking afforestation, protecting natural heritage areas, exploring opportunities for forest carbon management to increase carbon uptake, and promoting the increased use of wood products over energy-intensive, non-renewable alternatives.
- Help resource users and partners participate in a carbon offset market, by working with our partners to ensure that a robust trading system is in place based on rules established in Ontario (and potentially in other jurisdictions), continuing to examine the mitigation potential of forest carbon management in Ontario, and participating in the development of protocols and policies for forest and land-based carbon offset credits.

Theme 3: Help Ontarians Adapt
MNR will provide advice and tools and techniques to help Ontarians adapt to climate change. Strategies include:

- Maintain and enhance emergency management capability to protect life and property during extreme events such as flooding, drought, blowdown and wildfire.
- Use scenarios and vulnerability analyses to develop and employ adaptive solutions to known and emerging issues.
- Encourage and support industries, resource users and communities to adapt, by helping to develop understanding and capabilities of partners to adapt their practices and resource use in a changing climate.
- Evaluate and adjust policies and legislation to respond to climate change challenges.

Potential Effects of Climate Change and Adaptive Strategies for Lake Simcoe and the Wetlands and Streams Within the Watershed

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Summary

Changes in air temperatures, precipitation patterns, and extreme weather events associated with climate change have and will continue to influence aquatic ecosystems. Increased water temperatures, changes in the timing of the spring freshet, the duration of ice-cover, and the composition of wetlands have been already documented in several systems. Lake Simcoe and the wetlands and streams within the Lake Simcoe Watershed are also being affected by climate change. The objectives of this study were to (1) use ecological indicators to assess the potential effects of climate change and (2) apply those results to inform the development of a climate change adaptation strategy for aquatic ecosystems within the Lake Simcoe Watershed. For each ecosystem, physical habitat changes associated with climate change were paired with a biological indicator. Results indicated that 89% of the wetlands within the watershed will be vulnerable to drying and shrinkage due to projected increases in air temperature and decreases in precipitation. By 2100, stream temperatures may increase as much as 1.3°C above present conditions and suitable habitat for coldwater stream fish distributions may decrease in the 14 sub-watersheds in which they occur. Suitable thermal habitat for lake-dwelling, coldwater species such as lake trout may be reduced by 26%. These results do not account for other anthropogenic stressors such as groundwater withdrawals, stream regulation, or pollution that may exacerbate changes in the quality and quantity of aquatic habitats. Several recommendations are provided to help natural asset managers mitigate or adapt to the effects of climate change on aquatic systems. These include limiting infilling and draining activities in wetlands, restoring or maintaining riparian buffers in streams, and regulating effluents and fishing in lakes.

Résumé

Effets potentiels du changement climatique et stratégies adaptatives pour le lac Simcoe ainsi que les terres humides et les cours d'eau du bassin versant

Les changements de la température de l'air, la configuration des précipitations et les phénomènes météorologiques extrêmes, associés au changement climatique, influencent les écosystèmes aquatiques et continueront de le faire. Une augmentation de la température de l'eau ainsi que des changements à l'égard du rythme des crues printanières, de la durée de la couverture glaciale et de la composition des terres humides ont tous déjà été observés dans plusieurs systèmes. Le lac Simcoe, les terres humides ainsi que les cours d'eau du bassin versant de ce lac sont également touchés par le changement climatique. La présente étude vise à (1) utiliser les bioindicateurs afin d'évaluer les effets potentiels du changement climatique et (2) appliquer les résultats obtenus dans l'élaboration d'une stratégie d'adaptation pour les écosystèmes aquatiques du bassin versant du lac Simcoe. Pour chaque écosystème, les changements de l'habitat physique, associés au changement climatique, ont été jumelés à un bioindicateur. Les résultats ont révélé que 89 % des terres humides du bassin versant seront vulnérables à la sécheresse et au rétrécissement en raison des prévisions d'augmentation de la température de l'air et de diminution des précipitations. D'ici 2100, les températures des cours d'eau pourraient augmenter de 1,3 °C par rapport aux conditions actuelles et l'habitat adéquat pour les distributions des poissons d'eaux froides pourrait diminuer dans les 14 sous-bassins-versants dans lesquels elles sont présentes. La niche thermique adéquate pour les espèces de poissons d'eaux froides habitant les lacs, comme le touladi, pourrait diminuer de 26 %. Ces résultats ne tiennent pas compte des autres stresseurs anthropiques, comme le tarissement de l'eau souterraine, la régulation des cours d'eau et la pollution, qui peuvent exacerber les changements à l'égard de la qualité et de la

quantité des habitats aquatiques. Plusieurs recommandations sont fournies pour aider les gestionnaires des biens naturels à atténuer ou à adapter les effets du changement climatique sur les systèmes aquatiques. Celles-ci comprennent des restrictions à l'égard des activités de remplissage et de drainage dans les terres humides, la restauration ou le maintien de zones tampons riveraines dans les cours d'eau ainsi que la régulation des effluents et de la pêche dans les lacs.

Acknowledgements

This study was made possible by funding from the Ontario Ministry of Natural Resources and Ontario Ministry of the Environment - Lake Simcoe Climate Change Adaptation Strategy. Advice and data were kindly provided by Aaron Walpole, Bird Studies Canada, Pilar Hernandez, Joelle Young, Eleanor Stainsby, Jenny Winter, Jason Borwick, Victoria Kopf, and David Evans. Bastian Schmidt provided technical GIS advice. Dan McKenney, Paul Gray, Al Douglas, Gary Nielsen, Chris Lemieux, and Vidya Anderson provided climate data and/or coordinated the completion of vulnerability analyses in support of the Lake Simcoe Climate Change Adaptation Strategy. I thank Paul Gray, Ken Minns, and Lisa Buse for reviewing earlier versions of the report.

Foreword

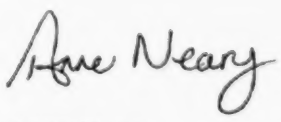
In a rapidly changing climate, decision-makers require a sense of the vulnerability of ecological and social systems to create goals and objectives for the future and propose actions to reduce or eliminate that vulnerability. In this context, vulnerability is the degree to which a system is susceptible to, or unable to cope with, the adverse effects of climatic change. In a world where climate change and other stressors are affecting natural and social systems, resource managers are working to integrate climate models (top-down projections of possible future climates) with vulnerability analyses (bottom-up assessments of how species and systems might be affected) to inform decision-making.

Climate models are projections rather than predictions: they require us to make assumptions based on best available information at the time. There is inherent uncertainty in these projections that derives from the degree of uncertainty in the assumptions. In addition, the response of Earth's climate to future greenhouse gas emissions is uncertain, and shifts in human behaviour in response to a changing climate and corresponding reductions to the rate and volume of greenhouse gas emissions are not fully known. Nevertheless, climate models provide a valuable tool to assess the vulnerability of ecosystems to a changing climate and assist resource managers in deciding on actions to improve ecosystem resilience and adaptation.

Vulnerability analysis uses a suite of ecological and social indicators to provide information about how a system is responding to change. Some indicators, such as an animal's thermoregulatory tolerance, are species specific while others, such as water temperature, provide information about the changing dynamics of entire systems. With this knowledge, management actions can be used to reduce or eliminate the vulnerability or support adaptation. Effective monitoring to measure change is also necessary, and raises the question: "Will existing monitoring inform effective decision-making in a rapidly changing climate?" Accordingly, existing monitoring programs should be re-examined to ensure they include the climate sensitive indicators measured at a frequency and/or scale that is relevant to expected changes in climate.

In the absence of complete information, vulnerability assessments are based on a variety of qualitative (e.g., expert opinion solicited during workshops) and quantitative (e.g., measures of species phenotypic and genetic plasticity) indices. These indicators can support practitioners' planning needs. As with any adaptive management process, ongoing assessment and modification are necessary as new information emerges.

Vulnerability assessment techniques continue to evolve and it is important for practitioners to learn by doing and to pass on knowledge gained. Accordingly, this and other vulnerability assessments have been prepared using the best available information under the circumstances (e.g., time, financial support, and data availability). We include these in our research report series to support MNR and others engaged in adaptive management. Collectively these assessments can inform decision-making, enhance scientific understanding of how natural assets respond to climate change, help practitioners design their own vulnerability assessments, and help resource management organizations establish research and monitoring needs and priorities.



Anne Neary
Director, Applied Research and Development Branch

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Introduction

Climate change is affecting aquatic ecosystems around the world. Water quality and quantity reflect changes in air temperature, precipitation, and extreme weather events associated with a changing climate (Durance and Ormerod 2007). Human activities such as river regulation, groundwater withdrawal, shoreline development, and point and non-point source pollution further stress these ecosystems.

The effects of climate change in wetlands are variable and depend on the conditions in the surrounding watershed and the sources of water. For example, changes in precipitation patterns will significantly affect the water budgets of bogs where the main source of water is precipitation. In fens, where water influx comes mainly from groundwater, effects will depend on the amount of precipitation, recharge rates, and geomorphology of the system (Mortsch et al. 2006).

In streams and rivers (hereafter all flowing waters are called streams) long-term increases in water temperatures and changes in stream biota have been detected (Durance and Ormerod 2007). In Ontario, warmer in-stream temperatures will provide more suitable habitat for species that prefer warmer temperatures throughout the ice-free season but may limit the distribution of other species that prefer cooler temperatures (Chu et al. 2008). Climate change may also alter the timing of the spring freshet and disrupt annual stream flow patterns (Mohseni et al. 2003).

The magnitude of change in lake ecosystems depends on the surrounding climate and the ecology of the system. In the Great Lakes region, mean annual air temperature increased at an average rate of 0.037°C annually between 1968 and 2002, resulting in a total increase of 1.3°C. Surface water temperature during August has been rising at annual rates of 0.084°C (Lake Huron) and 0.048°C (Lake Ontario) resulting in increases of 2.9°C and 1.6°C, respectively (Dobiesz and Lester 2009). Throughout Ontario, drier conditions, higher air temperatures, and reduced spring winds could lead to overall reductions in lake volume, warmer surface water temperatures, shallower thermoclines in stratified lakes, longer ice-free and stratification periods, longer growing seasons, and greater risk of hypoxia (Dove et al. 2011).

While there is widespread agreement about the need to recognize and prepare for climate change, and to develop and integrate risk management strategies into current and new programs, climate-sensitive adaptive processes are only now being designed and tested. An adaptive management process involves several steps: assessing readiness and capacity to respond, analyzing vulnerability to identify and prioritize adaptation needs, developing adaptation strategies and monitoring programs to measure adaptation success and to determine if vulnerabilities have been reduced or eliminated (Figure 1).

Climate change models project that air temperatures will increase throughout the entire Lake Simcoe Watershed with regional changes in precipitation patterns (McKenney et al. 2010). These changes will likely affect the aquatic ecosystems within the watershed. Based on the vulnerability and adaptation framework, the main objective of this study was to use vulnerability indicators for Lake Simcoe and the wetlands and stream ecosystems within the watershed to quantify the sensitivity of each system to climate change. In this report, I present results of a vulnerability assessment completed using selected indicators in support of the Lake Simcoe Climate Change Strategy called for in the Lake Simcoe Protection Plan (Government of Ontario 2009) by the Expert Panel on Climate Change Adaptation (2009) and Ontario's Adaptation Strategy and Action Plan: 2011-2014 (Government of Ontario 2011). These results were used to develop adaptation strategies for each ecosystem and inform the adaptive strategic planning process.

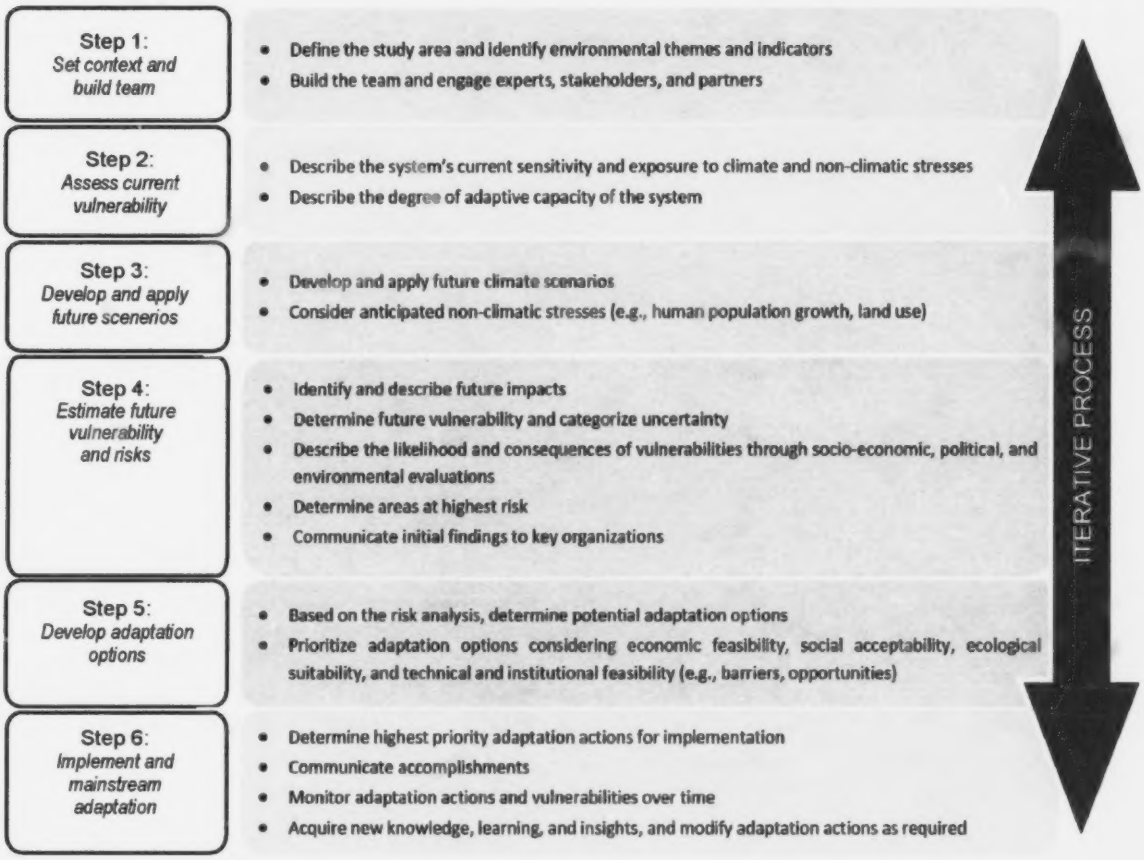

Step 1:
Set context and build team
Define the study area and identify environmental themes and indicators
Build the team and engage experts, stakeholders, and partners
Step 2:
Assess current vulnerability
Describe the system's current sensitivity and exposure to climate and non-climatic stresses
Describe the degree of adaptive capacity of the system
Step 3:
Develop and apply future scenerios
Develop and apply future climate scenarios
Consider anticipated non-climatic stresses (e.g., human population growth, land use)
Step 4:
Estimate future vulnerability and risks
Identify and describe future impacts
Determine future vulnerability and categorize uncertainty
Describe the likelihood and consequences of vulnerabilities through socio-economic, political, and environmental evaluations
Determine areas at highest risk
Communicate initial findings to key organizations
Step 5:
Develop adaptation options
Based on the risk analysis, determine potential adaptation options
Prioritize adaptation options considering economic feasibility, social acceptability, ecological suitability, and technical and institutional feasibility (e.g., barriers, opportunities)
Step 6:
Implement and mainstream adaptation
Determine highest priority adaptation actions for implementation
Communicate accomplishments
Monitor adaptation actions and vulnerabilities over time
Acquire new knowledge, learning, and insights, and modify adaptation actions as required
ITERATIVE PROCESS

Figure 1. *A conceptual framework to help determine organizational readiness, complete vulnerability analyses, and develop, implement, monitor, and adjust adaptation options as required (Source: Gleeson et al. 2011).*

Study Area: The Lake Simcoe Watershed

The Lake Simcoe Watershed encompasses 289,900 ha and is inhabited by more than 350,000 people (Figure 2). Lake Simcoe is one of the largest inland lakes in Ontario, encompassing 72,200 ha. In the last 30 years, excessive phosphorus loading was the leading source of pollution, but current levels are lower than those of the 1980s, water clarity is increasing, and the benthic macroinvertebrate community is in good condition (LSRCA 2008). Populations of coldwater fish species such as lake trout (*Salvelinus namaycush*) and lake whitefish (*Coregonus clupeaformis*) are sustained by annual stocking programs while warmwater (e.g., largemouth bass, *Micropterus salmoides*) and coolwater (e.g., yellow perch, *Perca flavescens*) fish populations are relatively stable (Scott et al. 2005; Robillard 2010a, b). Watershed wetlands include bogs (25 ha), fens (450 ha), marshes (~4,490 ha), and swamps (~30,620 ha) (Beacon Environmental and LSRCA 2007, OMOE 2010). The watershed contains approximately 3,900 km of stream channels. Stream health indicators (e.g., forest cover) are negatively correlated with human development (LSRCA 2008).

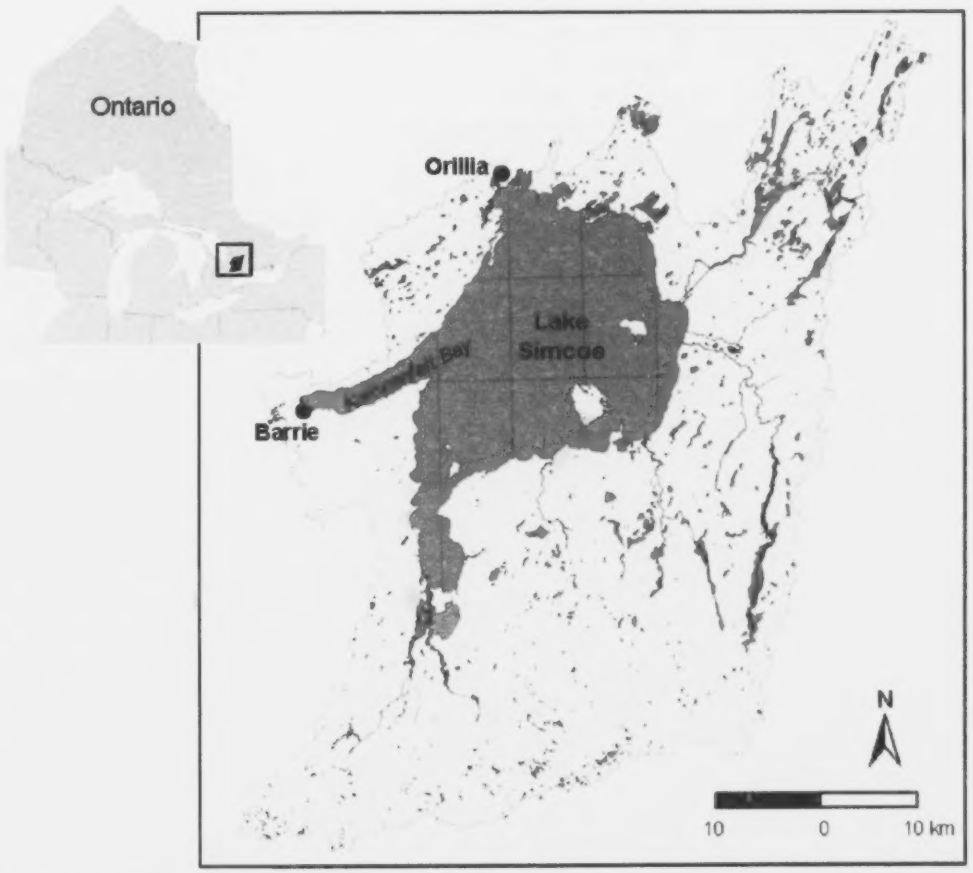
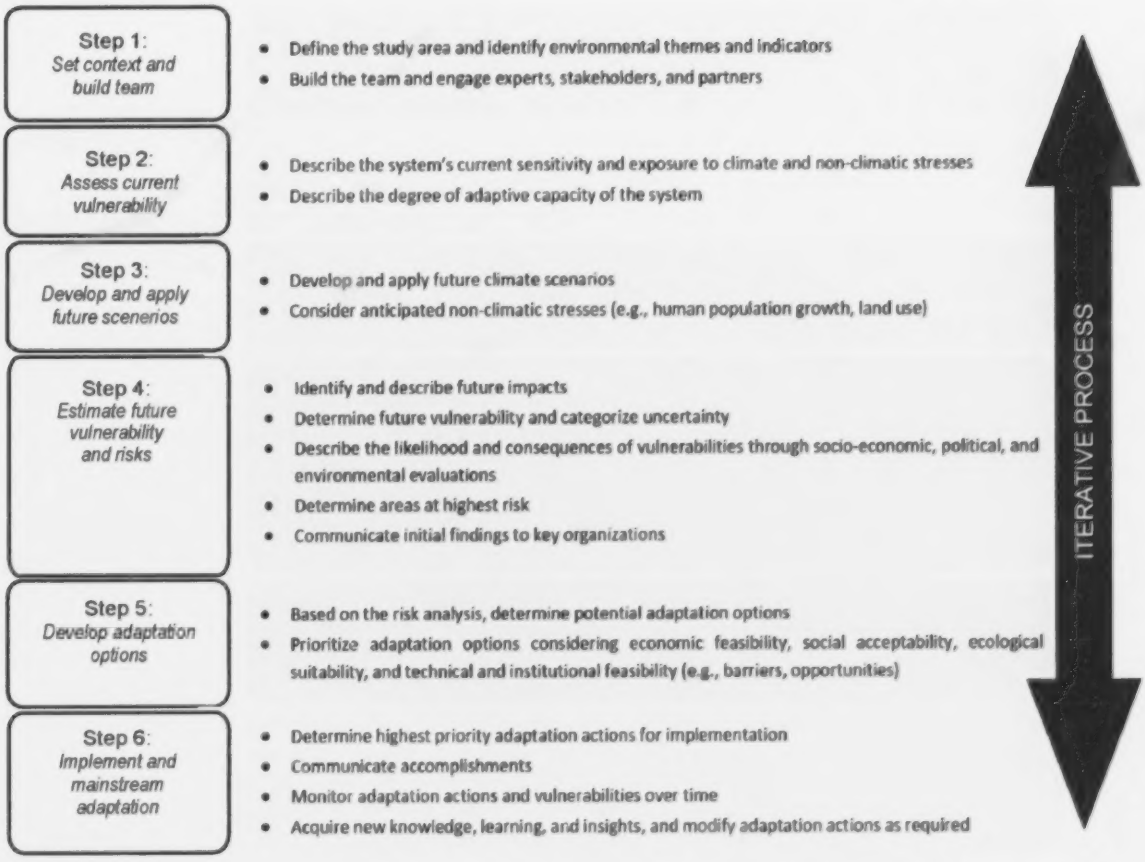


Figure 2. *Location of the Lake Simcoe watershed in Ontario.*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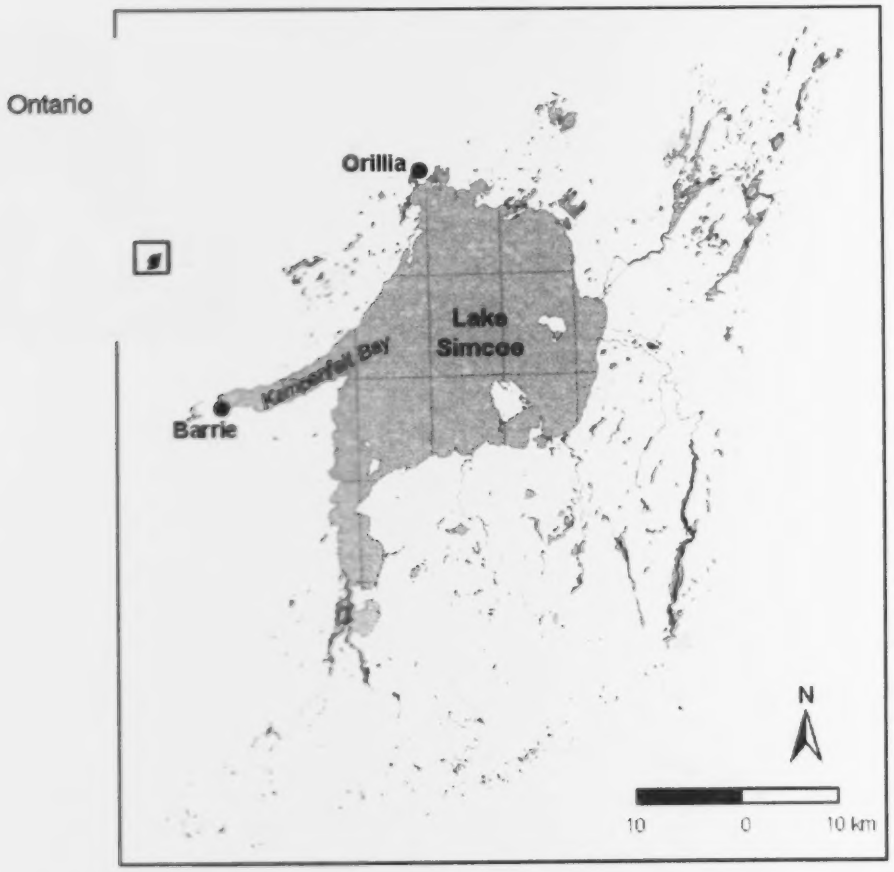

Figure 2. *Location of the Lake Simcoe watershed in Ontario.*

Methods

Different indicators were used to forecast the effects of climate change on the wetland, stream, and lake ecosystems of the Lake Simcoe Watershed. For each ecosystem, changes in a physical habitat indicator (derived from climate and landscape variables) were paired with a biological metric that served as an example of the biological consequence of those habitat changes. Current climate conditions were estimated using the 1971-2000 Canadian Climate Normals data. Forecasts were made using newly developed or existing models that relate the biological metrics to habitat variables. The Canadian Global Climate Model 2 (CGCM2) with the A2 emissions scenario (economically as opposed to environmentally driven scenario) for the 2011-2040, 2041-2070 and 2071-2100 time periods were used to project future climate. This scenario was selected because it provides a "business-as-usual" assessment. It is important to note that if atmospheric greenhouse gas emissions are lower than those projected by the A2 scenario natural asset managers can modify the statement of effects and adjust adaptation programs accordingly. Summaries of present and potential climatic conditions are provided in McKenney et al. (2010).

Wetlands

Wetland vulnerability

Marshes, swamps, bogs, and fens occur throughout the Lake Simcoe Watershed. The vulnerability of each of these wetland types to climate change was assessed using projected air temperature, precipitation, and groundwater discharge potential based on a *base flow index* that relates groundwater to underlying surficial geology (Neff et al. 2005). In this index, values closer to 0 indicate little groundwater flow. The climate and landscape variables were selected to evaluate wetland vulnerability to climate change because changes in any one will affect the water budget. For this indicator, vulnerability was defined as degraded quality or loss due to drying resulting from increased evaporation at warmer air temperatures, water loss due to decreased precipitation, and/or low groundwater inflow.

The change in growing season (April to September) air temperatures and total precipitation from current conditions to the 2011-2040, 2041-2070, and 2071-2100 periods were provided by McKenney et al. (2010). The wetland polygons were spatially joined to the air temperature and precipitation projections in ArcGIS® 9.0 (Environmental Systems Research Institute Inc., Redlands, California, USA). Under the A2 scenario, air temperatures will increase throughout the watershed while total precipitation will either remain the same or decrease. Even if total growing season precipitation were to remain constant, seasonal precipitation patterns (e.g., the timing of spring rains) may change and affect ecosystem function in the watershed. Groundwater discharge potential was held constant during the modelling because it may be years before changes in groundwater quantity, recharge rates, and timing of discharge occur and even longer before they affect the system (Chu et al. 2008). The area-weighted base flow index values for each of the wetland polygons were calculated using zonal statistics in ArcGIS.

The range of change in temperatures, precipitation patterns, and groundwater were used to generate vulnerability matrices for each time period (Table 1). The underlying premise was that comparatively greater increases in air temperature and decreases in precipitation and groundwater inflow are associated with greater vulnerability to climate change.

Table 1. *Vulnerability matrices for wetlands in the Lake Simcoe watershed as a result of base flow index value (groundwater discharge potential), and changes in April to September air temperatures and total precipitation projected by the Canadian Global Climate Model 2 (CGCM2) A2 scenario for the 2011-2040, 2041-2070, and 2071-2100 time periods.*

Time period	Base flow index value	Increase in air temperature (°C)	Decrease in precipitation (mm)	Vulnerability
2011-2040	0.00-0.41	0.30-0.56	0-20	mid
	0.42-0.82	0.30-0.56	0-20	low
	0.00-0.41	0.57-0.83	30-40	high
	0.42-0.82	0.57-0.83	30-40	mid
	0.00-0.41	0.30-0.56	30-40	high
	0.42-0.82	0.30-0.56	30-40	mid
	0.00-0.41	0.57-0.83	0-20	mid
	0.42-0.82	0.57-0.83	0-20	low
2041-2070	0.00-0.41	2.71-3.00	0-25	high
	0.42-0.82	2.71-3.00	0-25	low
	0.42-0.82	3.00-3.30	26-50	mid
	0.00-0.41	3.00-3.30	26-50	high
	0.42-0.82	2.71-3.00	26-50	mid
	0.00-0.41	2.71-3.00	26-50	high
	0.00-0.41	3.00-3.30	0-20	high
	0.42-0.82	3.00-3.30	0-20	mid
2071-2100	0.00-0.41	4.98-5.02	0-20	high
	0.42-0.82	4.98-5.02	0-20	mid
	0.42-0.82	5.03-5.71	26-50	high
	0.00-0.41	5.03-5.71	26-50	high
	0.00-0.41	4.98-5.02	26-50	high
	0.42-0.82	4.98-5.02	26-50	high
	0.00-0.41	5.03-5.71	0-20	high
	0.42-0.82	5.03-5.71	0-20	mid

Wetland indicator bird species distributions

In 2006, Mortsch et al. developed a vulnerability index for wetland bird species based on their life history characteristics and habitat requirements. Here, pied-billed grebe (*Podilymbus podiceps*) was selected as the indicator species to examine the potential effects of climate change on wetland bird distributions because it is found within the Lake Simcoe watershed and is one of the species most sensitive to climate change (Mortsch et al. 2006). The wetland vulnerability maps were overlaid onto the present distribution map of the pied-billed grebe (Bird Studies Canada 2010) to determine how its range might be restricted by the degradation or loss of wetlands due to climate change.

Streams

In-stream thermal regimes

Stream water temperature was selected as a climate change indicator because it is directly related to air temperature (Mohseni et al. 1998), significantly affects overall water quality (Ducharne 2008), fish growth rates (Allen et al. 2006), timing of fish spawning events (Connor et al. 2003), and the distribution of organisms in stream ecosystems (Caissie 2006). Maximum weekly water temperature (MWT) was used to represent in-stream temperature because it quantifies the warmest, and potentially most biologically limiting, condition in the streams.

A model developed by Baird and Associates (2006) for the East Holland River was used to predict MWT in streams for the 2011-2040, 2041-2070, and 2071-2100 time periods. Given that air temperature and in-stream water temperature are related, air and water temperature data available from 47 sites were used to validate the

model (root mean square error = -0.5°C ± 2.5°C). The Baird model and the air temperature scenario data were used to predict MWT in the streams throughout the watershed.

Likelihood that streams in the sub-watersheds will retain cold-water fish species

Chu et al. (2008) developed an index of the likelihood that quaternary watersheds in southern Ontario will retain coldwater stream fish species (e.g., brook trout, *Salvelinus fontinalis,* and mottled sculpin, *Cottus bairdii*) (Table 2). This index is based on maximum air temperature and groundwater discharge potential and indicates that watersheds with high groundwater discharge potential could provide thermal refugia for coldwater species during a period of rapid climate change.

Using ArcGIS, area-weighted maximum air temperature and groundwater discharge potential under the 1971-2000 climate normals and the CGCM2 A2 scenario for 2011-2040, 2041-2070, and 2071-2100 were calculated for the 14 sub-watersheds that presently support coldwater stream fish species. These values were compared to the likelihood index to rank the watersheds by their potential (low, mid, and high) to retain coldwater species.

Table 2. *Likelihood that watersheds will retain coldwater species in 2055 based on maximum air temperature projections from the Canadian Global Climate Model 2 A2 scenario and groundwater discharge potential (Source: Chu et al. 2008).*

Attribute	Likelihood of retaining cold-water species		
	Low	Mid	High
Maximum air temperature (°C)	>29.34	29.34-28.49	<28.49
Base flow index value	<0.36	0.36-0.54	>0.54

Lake Simcoe

Lake temperature profiles

Lake water temperature was selected as an indicator of climate change because it will be directly affected by changes in air temperature (Trumpickas et al. 2009). Temperature profile data (temperatures at 1 m depths) for the OMOE station K42 in Kempenfelt Bay (the deepest part of the lake) were used to complete the analysis. These temperature data spanned 1980 to 2009; end of summer (September 15th) temperatures were used to calculate the current mean temperature profile. That is, temperatures at each 1 m depth interval were averaged across the 1980 to 2009 period to produce a single temperature profile that represented the average end of summer temperature profile for K42. End of summer temperatures represent the critical time when temperature and dissolved oxygen content could limit coldwater species distributions. Changes in the thermal profile of the lake were projected using a model developed by Mackenzie-Grieve and Post (2006) (Equation 1) parameterized to the mean temperature profile for K42.

$$T = T_b + T_d((D^{STEEP})/(Z_{th}^{STEEP} + D^{STEEP})) \qquad \text{(Eq. 1)}$$

where T is the temperature (°C) at a given depth, T_b is the bottom temperature (°C) of the lake (profile), T_d is the difference in temperature from the surface to the bottom (i.e., $T_d = T_{surface} - T_b$) of the profile, D is the given depth (m) in the profile, Z_{th} is the thermocline depth (m), and STEEP = -5.01, and is a unitless parameter describing the shape of the thermocline. For K42 these parameter values were T_b = 8.6, T_d = 9.9 (18.5-8.6), Z_{th} = 17.78 (the mean thermocline depth for the 1980 to 2009 period; the thermocline was defined as the mean depth of the metalimnion (middle layer in a lake) defined as the depths at which temperatures changed >1°C·m^{-1}).

Mean September air temperature data from 1980 to 2009 were attained from the Barrie Water Pollution Control Centre climate station and used to calculate water temperatures at the lake surface from air temperatures ($y = 0.63x + 8.28$, $r^2 = 0.37$, $p = 0.001$). This equation was used to predict surface water temperatures under the CGCM2 A2 scenario for the 2011-2040, 2041-2070, and 2071-2100 periods. These surface water temperature values were entered into Equation 1 to predict future temperature profiles for Lake Simcoe.

Thermal habitat volume for lake trout

Coldwater species and their preferred habitats are likely to be more negatively affected by climate change than coolwater and warmwater species and their habitats (Chu et al. 2005, Ficke et al. 2007). Using Kempenfelt Bay as an indicator of the thermal conditions in the entire lake, suitable thermal habitat volume for lake trout (8 to 12°C) was calculated from a hypsographic curve (whole lake volume at each 1 m depth stratum) and the current, 2011-2040, 2041-2070, and 2071-2100 temperature profiles.

Results

Ninety per cent of the swamps, 84% of the marshes, 50% of the fens, and 100% of the bogs may be highly vulnerable to drying under the increased air temperature, decreased precipitation, and changes in groundwater conditions by 2100 (Table 3, Figure 3). Based on the assumptions in the A2 scenario, the availability of suitable habitat for wetland-dependent species will decrease. Pied-billed grebe distributions may be reduced by 84% by 2071-2100 because most of the wetlands it currently inhabits may be degraded or lost (Figure 3).

Maximum weekly stream temperatures across the watershed will likely increase with climate change but the regional pattern may remain the same (i.e., warm areas such as the southwestern region of the watershed may continue to be warmer than the northeastern region) (Figure 4). Coldwater fish species are present in 14 of the 18 sub-watersheds (Figure 5). Under the CGCM2 A2 scenario, coldwater species distribution within all of the watersheds may be reduced by 2100 (Figure 5). Sub-watersheds with higher groundwater inflows and comparatively lower increases in air temperature have the highest potential for retaining coldwater species (Table 4).

Table 3. *Total area (ha) and vulnerabilities of swamps, marshes, bogs, and fens in the Lake Simcoe Watershed to air temperature, precipitation, and groundwater changes expected under the Canadian Global Climate Model 2 (CGCM2) A2 scenario.*

Wetland type	Current area (ha)	Vulnerability	Area (ha) by time period		
			2011-2040	2041-2070	2071-2100
Swamp	30612	High	4507	17354	27457
		Mid	8693	12492	3151
		Low	17412	767	4
Marsh	4485	High	117	2255	3781
		Mid	2646	2193	704
		Low	1722	37	—
Bog	25	High	—	25	25
		Mid	25	—	—
		Low	—	—	—
Fen	450	High	5	190	227
		Mid	199	252	223
		Low	246	8	—

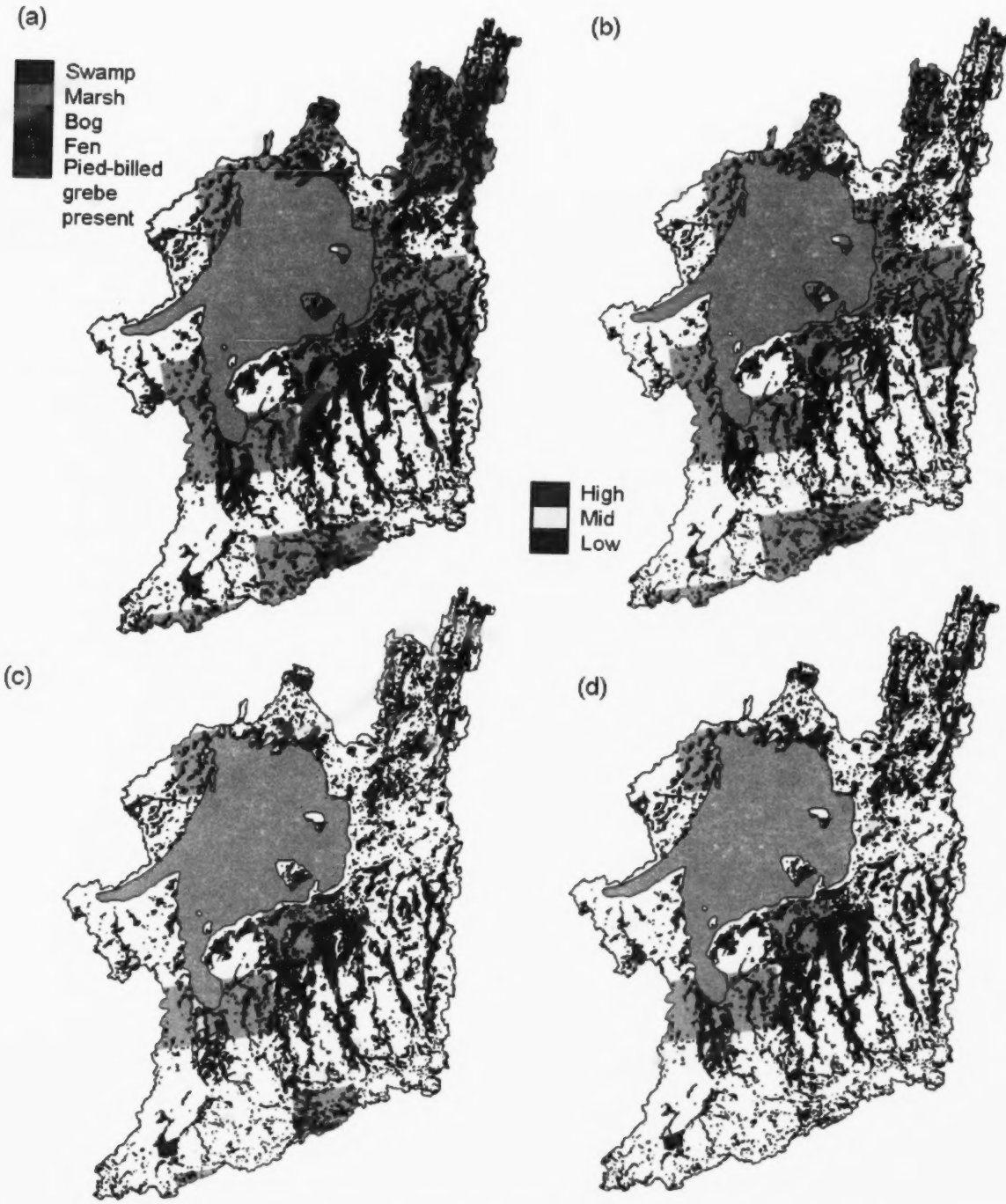

Figure 3. *Current distribution of swamps, marshes, bogs, fens, and pied-billed grebes within the Lake Simcoe Watershed and their vulnerability to groundwater discharge potential and changes in air temperature and precipitation associated with climate change under the Canadian Global Climate Model 2 A2 scenario for (a) current, (b) 2011-2040, (c) 2041-2070, and (d) 2071-2100 time periods.*

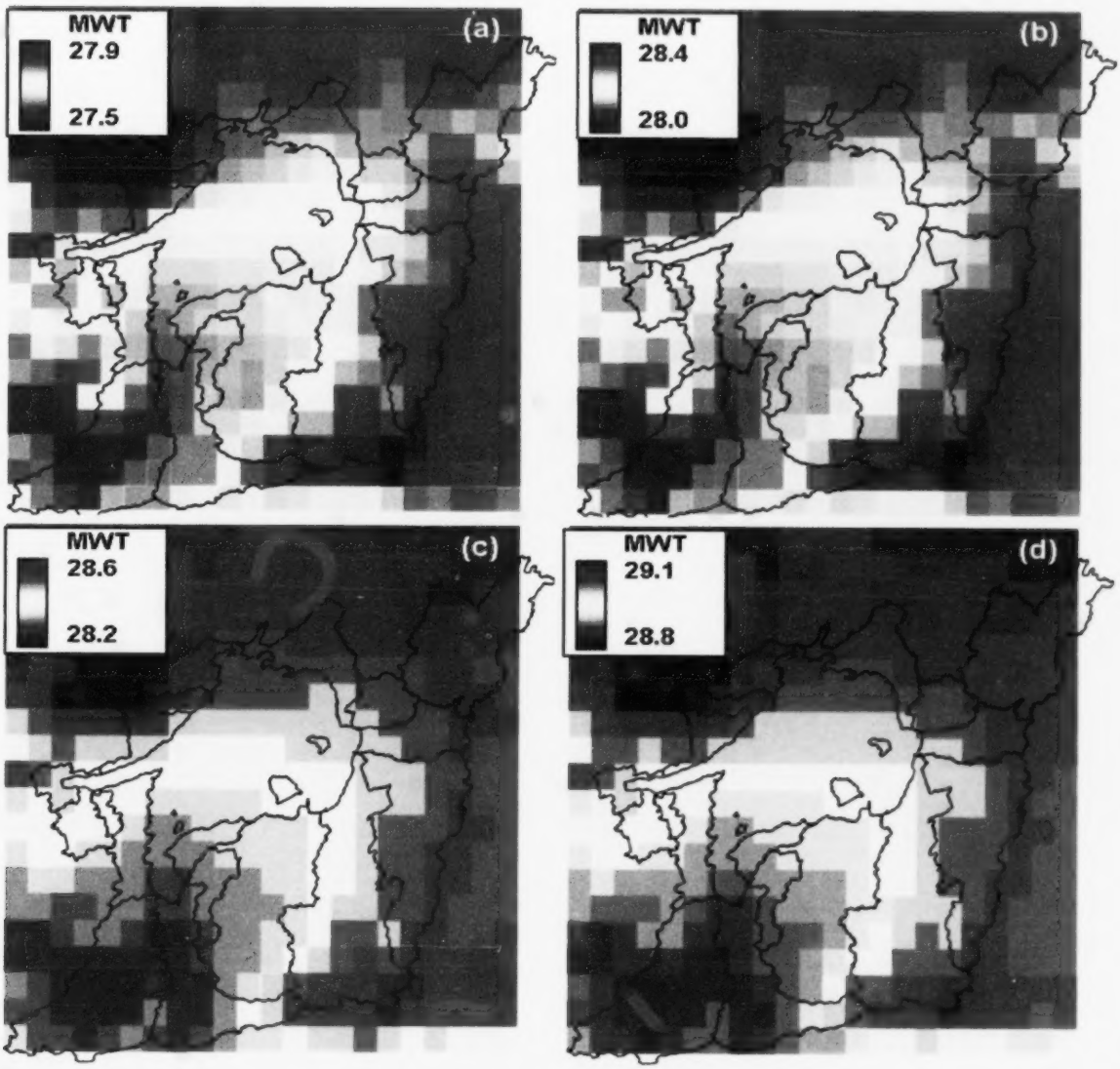

Figure 4. *Maximum weekly stream temperatures (MWT) in the Lake Simcoe watershed under (a) current, (b) 2011-2040, (c) 2041-2070, and (d) 2071-2100 air temperature projections of the Canadian Global Climate Model 2 A2 scenario.*

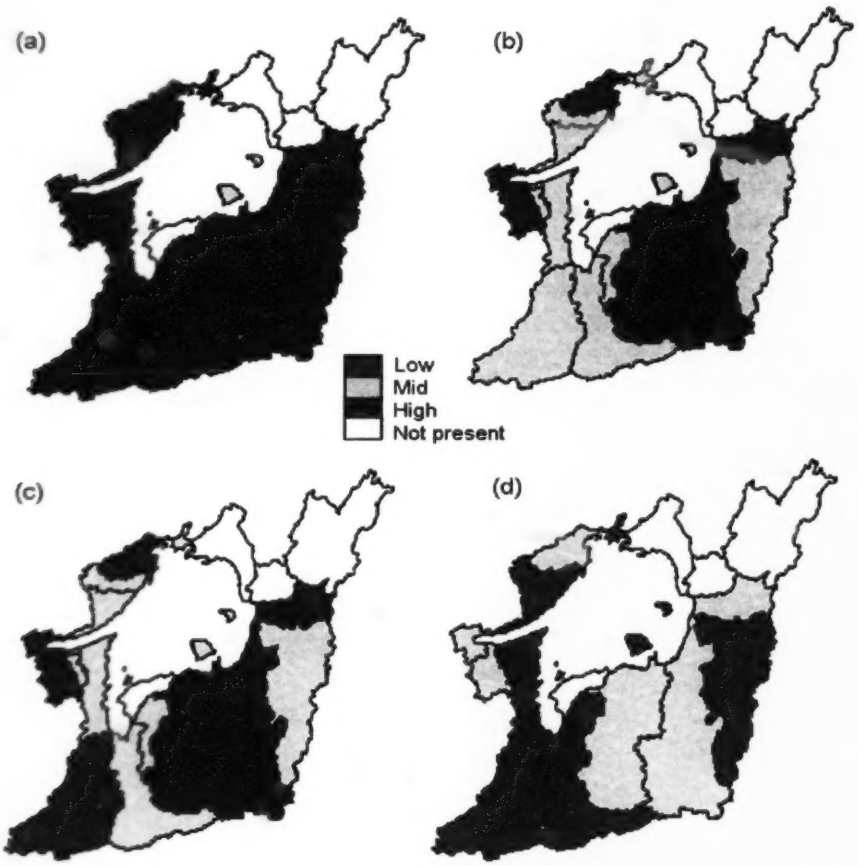

Figure 5. *Likelihood that watersheds will retain coldwater fish species under the (a) current, (b) 2011-2040, (c) 2041-2070, and (d) 2071-2100 air temperature projections of the Canadian Global Climate Model 2 A2 scenario.*

Table 4. *Maximum air temperature and groundwater discharge potential characteristics of the 14 sub-watersheds that support coldwater stream fish species in the Lake Simcoe Watershed. Base flow index values are measures of groundwater discharge potential; values close to 1 indicate high groundwater inflows.*

Sub-watershed	Base flow index value	Maximum air temperature (°C) by time period		
		2011-2040	2041-2070	2071-2100
Barrie Creeks	0.663	25.79	27.51	28.14
Beaver River	0.426	25.74	27.40	28.01
Black River	0.610	25.90	27.71	28.35
East Holland River	0.453	25.91	27.86	28.49
Hawkestone Creek	0.443	25.48	27.20	27.75
Hewitts Creek	0.350	25.84	27.62	28.20
Innisfil Creeks	0.426	25.90	27.74	28.34
Lovers Creek	0.594	25.83	27.63	28.22
Maskinonge River	0.532	25.95	27.81	28.44
Oro Creeks North	0.542	25.56	27.23	27.81
Oro Creeks South	0.329	25.67	27.44	28.02
Pefferlaw Brook	0.582	25.76	27.44	28.07
West Holland	0.373	26.03	27.97	28.59
Whites Creek	0.616	25.78	27.40	28.02

Between 1980 and 2009, the surface water temperature in Lake Simcoe increased approximately 2°C (r^2 = 0.32, p = 0.001; Figure 6). During the same period, the thermocline of the lake has declined slightly, but thermocline depths are highly variable and the trend was not significant (r^2 = 0.03, p = 0.33; Figure 6). By 2100, surface water temperatures could increase by 2.4°C, with the greatest difference between present and future water temperatures occurring within the epilimnion (top and warmest layer of water in a lake). Temperatures in the hypolimnion (bottom and coldest layer of water in a lake) are projected to increase by 0.6°C (Figure 7). Using Kempenfelt Bay as an indicator of the thermal conditions in the entire lake, suitable thermal habitat for lake trout (8 to 12°C) may decline by 2 m from 2011-2040 to 2071-2100, which could result in a 26% decrease in the volume of suitable thermal habitat by 2100 (Table 5).

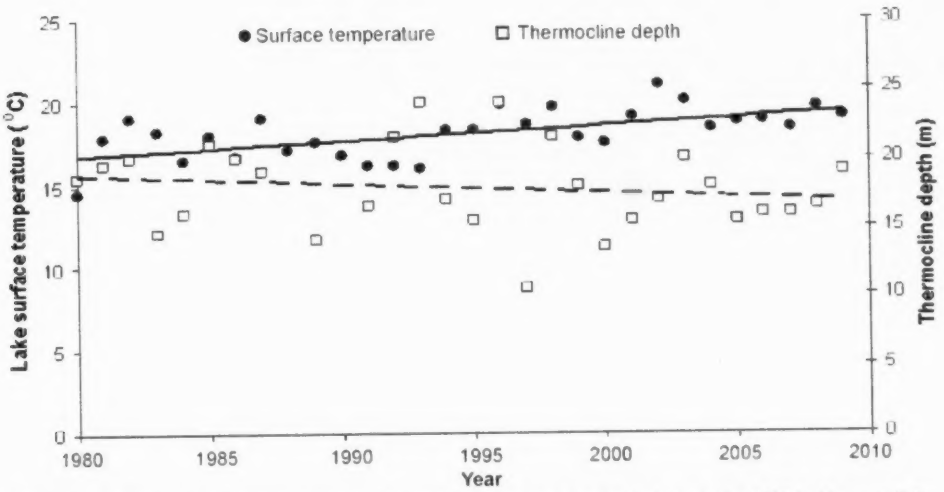

Figure 6. *Surface water temperatures (°C) and thermocline depths (m) at station K42 in Kempenfelt Bay, Lake Simcoe from 1980 to 2009.*

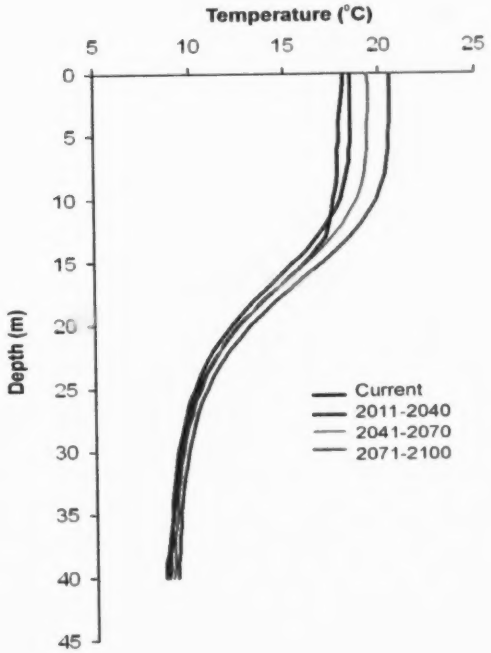

Figure 7. *Estimated temperature profile for Kempenfelt Bay on September 15 under current and future climates based on the Canadian Global Climate Model 2 A2 and the temperature profile model outlined in Equation (1).*

***Table 5**. Suitable depths and thermal habitat volumes for lake trout in Lake Simcoe projected by the Canadian Global Climate Model 2 A2 scenario by time period (based on Kempenfelt Bay temperature profiles with the lake bottom ≈ 40 m).*

Habitat component	Time period			
	Present	2011-2040	2041-2070	2071-2100
Thermally suitable depths (m)	21 m to lake bottom	21 m to lake bottom	22 m to lake bottom	23 m to lake bottom
Thermal habitat volume (ha*m)	143,500	143,500	124,700	105,800

Discussion and Recommendations

Study results are presented in the context of the literature and current understanding of the Lake Simcoe Watershed to provide recommendations for future research and monitoring activities as well as inform the adaptive strategic planning process.

Research

Wetlands

The Ontario Ministry of Natural Resources is updating wetland baseline data for the Lake Simcoe watershed in support of work to identify, protect, and restore high priority habitats that help reduce nutrients affecting the lake (Environment Canada 2010). The wetland vulnerability indicator assessed in this study ranked the vulnerability of individual wetlands to projected increases in air temperatures and decreases in precipitation and groundwater inflow based on projections generated by the CGCM2 A2 scenario. Results indicated that 89% of the wetlands may be of decreased quality and extent by 2100 due to changes in water budgets. Loss or degradation of wetland habitat may reduce populations of wetland-dependent species such as the pied-billed grebe.

The strengths of the analyses reported here are that they:

- Incorporate the dominant physical variables (air temperature, precipitation and groundwater inflows) that influence wetlands (Mortsch et al. 2006)
- Offer easily interpretable guides for setting priority areas for wetland conservation
- Provide a framework for assessing how wetland changes may influence habitat availability and the distribution of wetland-dependent species

Several uncertainties require additional research given expected changes in climate, including:

- The amount of change that can be expected in wetland extent
- The types of shifts in wetland plant composition that may occur
- Whether birds will move to less optimal habitats or adapt to changing wetland conditions
- The cumulative effects of other factors that influence wetland vulnerability such as infilling and draining

In this study, each wetland was treated as a unit and assigned a vulnerability ranking. However, entire wetlands may not be affected uniformly. For example, drying or shrinking may occur around the edges only leaving the middle intact. And although plant composition data were not available for this study, a shift will likely occur in some wetlands. For example, marshes may become more swamp-like as they are colonized by woody plant species (swamps are generally defined as plant communities with at least 25% woody cover). As well, it was assumed that bird species will move out of unsuitable areas and the possibility that other species

may occupy these same areas or that existing wetland species may adapt to the changing conditions was not considered. More detailed estimates of how the wetlands will change (in terms of extent and plant community composition) would provide more realistic projections of how species distributions may change given expected changes in climate.

In addition, non-climatic stressors such as peat extraction, agricultural activities, and urban development also affect wetland conditions. Run-off from urban and agricultural lands may contain pollutants, nutrients, and sediments that can compromise water quality. This in turn negatively affects plant growth, community composition, and overall availability of wetland habitats (Mortsch et al. 2006).

Streams

Streams in the Lake Simcoe watershed vary from those that are relatively undisturbed with an abundance of streamside vegetation, forest cover, and little impervious cover to those that are more disturbed with little streamside vegetation, an abundance of impervious cover, and little forest cover (Table 6). In this study, the potential effect of climate change on maximum stream temperatures was examined and results indicated that stream temperatures will increase with climate change and, as a result, coldwater fish species distributions may be reduced within the sub-watersheds by 2100.

Table 6. *Indicators used to assess stream ecosystem health in the 18 sub-watersheds of the Lake Simcoe watershed. Grading follows the conventional A to E, with A indicating good and E indicating poor values for the indicators. I/D = insufficient data, N/A = not available (Source: LSRCA 2008).*

Sub-watershed	Indicator							
	Streamside vegetation	Forest cover	Forest interior	Phosphorus concentration	Fish community	Benthic invertebrates	Hardened surfaces	Storm water
Barrie Creeks	E	C	E	I/D	C	C	E	E
Beaver River	B	C	D	A	C	B	A	E
Black River	A	A	A	B	C	B	A	D
East Holland River	C	B	C	C	C	B	D	D
Georgina Creeks	C	A	A	I/D	B	I/D	B	D
Hawkestone Creek	A	A	A	A	C	B	A	N/A
Hewitts Creek	C	C	D	I/D	C	B	B	A
Innisfil Creek	D	A	B	I/D	C	I/D	B	D
Lovers Creek	B	A	B	B	C	C	C	D
Maskinonge River	C	D	E	C	B	D	A	C
Oro Creeks north	A	A	A	I/D	C	A	B	E
Oro Creeks south	A	A	B	I/D	C	A	A	N/A
Pefferlaw River	A	A	A	B	B	C	A	N/A
Ramara Creeks	C	A	A	I/D	C	D	A	N/A
Talbot River	D	A	A	I/D	I/D	I/D	A	N/A
Uxbridge Brook	A	A	A	I/D	C	A	A	C
West Holland River	C	B	C	D	C	B	A	D
White's Creek	D	B	B	I/D	C	B	A	N/A

Uncertainties requiring additional research include that:

- Stream temperatures are more heterogeneous than the simplified approach used here
- Coldwater species are not uniformly distributed within the sub-watersheds
- Other factors influence species distributions in streams

Although air temperatures are a major driver, stream water temperatures are also influenced by land cover and the physical characteristics of the surrounding watershed. Chu et al. (2010) reported that stream temperatures in the Great Lakes Basin are related to surrounding riparian cover, forest cover, upstream water bodies, and air temperatures in the watersheds upstream of temperature sampling sites. Future research should involve a more detailed assessment of the spatial variability in stream temperatures as related to these watershed characteristics.

The current distribution map shows that coldwater species are present in 14 of the 18 sub-watershed but the species are not uniformly distributed within those watersheds. In most streams, especially in summer, coldwater species actively seek out the comparatively cooler headwaters or groundwater seeps (Power et al. 1999). In addition to temperature, habitat preferences for different substrates, vegetation, and flow regimes also affect coldwater species distributions in the sub-watersheds.

Other climate variables and human activities will compound the effects of climate on changes in stream habitats. Changes in rain patterns, groundwater recharge rates, and snow accumulation and melt patterns could also disrupt fluvial and thermal regimes in the streams. In 2008, the Lake Simcoe Region Conservation Authority found a negative correlation between stream health indicators and human development. Land use activities within the sub-watersheds significantly affect stream health through sedimentation, point and non-point source pollution, groundwater withdrawals, and stream flow regulation. The cumulative effects of different stressors and the habitat preferences of different stream fish species should be incorporated into future studies established to explore the potential effects of climate on stream ecosystems.

Lake Simcoe

Over the past few decades, Lake Simcoe has undergone significant ecological changes. Ecosystem health indicators in 2008 showed that phosphorus levels were lower than those recorded during the 1980s, dissolved oxygen content and water clarity were improving, the benthic invertebrate community was in good condition, and macrophyte plant biomass was increasing. Lake trout and lake whitefish have been sustained with annual stocking programs after declines in the 1960s. In response to recent signs of recovery (La Rose and Willox 2006), the lake trout stocking program has been scaled back to allow increased natural recruitment (Borwick et al. 2009). Populations of warmwater (e.g., largemouth bass) and coolwater species are relatively stable (Robillard 2010a, b).

The approach used in this study was a simple representation of lake temperatures and potential habitat changes associated with climate. Increased temperatures will benefit some fish species, such as largemouth bass and yellow perch, that prefer warmer temperatures and will reduce suitable thermal habitat for coldwater species such as lake trout. A reduction in lake trout habitat may have negative, density-dependent effects on its growth and survival, change its foraging behaviour, and alter the overall carrying capacity of Lake Simcoe for lake trout.

Several uncertainties that should be addressed in future studies include:

- The predicted temperature profiles represent the average thermal conditions in the lake
- Kempenfelt Bay was treated as the representative station for the temperature profile of the whole Lake but other factors known to influence the spatial variability of water temperatures (e.g., wind and lake morphometry) have not been included and should be
- Other factors that influence the availability of suitable habitat for different species (e.g., substrate and prey availability) have not been included
- The direct influence of climate change on lake species has not been assessed
- Lower trophic level dynamics also may change with climate

The projected temperature profiles were developed using the mean (average for 1980 to 2009) thermal profile for the lake, thus inter-annual variability in temperatures that will likely occur during the three time periods have not been addressed in this study. Future research should examine the influence of inter-annual variability in temperatures on available habitat and lake biota.

The deepest part of the Lake, Kempenfelt Bay, was used to model the thermal profiles and assess the changes in suitable habitat volume for September 15. To obtain a more accurate projection of suitable thermal habitat volume, the spatial and temporal variability in temperatures given expected climate change should be assessed. Future research should examine how these changes influence lake temperatures. A study is

underway to develop a detailed 3D thermo-hydrodynamic model for the lake using ELCOM (Estuary and Lake Computer Model (Hodges and Dallimore 2007) with Leon Boegman, Queen's University. This model will provide better estimates of the spatial and temporal variability in lake temperature under current conditions and could be used with climate projections to provide more detailed estimates of how water temperatures may change.

Water temperatures also vary seasonally. The model used in this study was developed using temperature profiles for the end of summer (September 15), which were assumed to represent the critical time when temperature and dissolved oxygen content limit coldwater species distribution. Although seasonal changes in lake temperatures were not included in this analysis, data from 1980 to 2009 indicate that the period of stratification in the lake has extended from 84 days in the 1980s to more than 100 days in the 2000s (Stainsby et al. 2011). Future research on the seasonal variability of water temperatures is needed to improve estimates of year-round thermal habitat for lake biota.

In addition to temperature, other factors such as substrate, vegetation, and water quality influence species distribution within the lake. As indicated previously, one of the most important variables is dissolved oxygen, which is particularly important in the hypolimnion where depletion at the end of the summer can limit species distribution, especially that of coldwater species such as lake trout (Evans 2007). Volume weighted hypolimnetic oxygen levels in September have increased from 3 mg per L during the 1980s and early 1990s (Evans 2007) to more than 5 mg per L in the last 5 years (Young et al. 2011). Further reductions in total phosphorus loading to 44 tonnes by 2045 (OMOE 2010, Young et al. 2011) are expected to support additional increases in oxygen levels. However, further research to examine how increases in the duration of stratification (Stainsby et al. 2011) may affect the availability of hypolimnetic oxygen for biota remains important as oxygen levels may be depleted to critical levels before they are replenished during the fall turnover.

Future research should also focus on direct linkages between fish species recruitment and climate. Casselman (2002) found that year-class strength of warmwater fish in Lake Ontario was positively correlated with July-August air temperatures, with El Niño years (1973, 1983, 1995) showing the greatest recruitment. Year-class strength of coolwater fish was curvilinearly related to midsummer temperatures while coldwater species such as lake trout showed poor emergence of fry in the spring when preceded by warm autumns and winters.

Lastly, climate change could also affect lower trophic levels in the Lake. The temporal overlap between zooplankton, on which planktivorous fish feed, and their prey, the phytoplankton, may be reduced (Winder and Schindler 2004). The earlier onset of stratification observed in Lake Simcoe (Stainsby et al. 2011) suggests that phytoplankton are likely to bloom earlier in the spring. This would result in lower food availability for zooplankton when their population is increasing thus lowering zooplankton densities in the spring/summer. In 2006, the offset between phytoplankton and zooplankton peaks was 45 days and zooplankton densities decreased from 1989 to 2001 (J. Young, OMOE, unpublished data). These results suggest that the lower trophic changes may be already occurring in Lake Simcoe. Further research is needed to assess the effects of climate change on potential food web changes.

Monitoring

Wetlands

Monitoring in wetland ecosystems should focus on (1) evaluating (for ecological significance) the 11,000 ha of wetlands that have not yet been evaluated and (2) conducting baseline inventories to assess species composition, particularly plant species, in the different wetlands. This would provide a base for more detailed assessments of plant community shifts that may be related to climate change.

Streams

Presently, 12 flow monitoring stations, 14 groundwater wells, 18 water quality stations, and several temperature data loggers are installed throughout the Lake Simcoe watershed. In addition, fish and benthic inventories are completed at several of these sites as part of the ecosystem indicator reporting (LSRCA 2008). The maintenance and possible expansion of these networks would provide valuable ongoing and long-term information to assess the effects of climate change on stream ecosystems.

Lake Simcoe

Various aspects of the lake ecosystem (e.g., water quality parameters, fish stock assessments) are monitored by several agencies working within the watershed. Monitoring for invasive species and climate-induced change could be integrated into existing programs.

Adaptation

Adapting to a changing climate will require integrated management actions that balance the continuation of ecosystem function with human activities. The human population within the Lake Simcoe watershed is projected to increase to 500,000 by 2031 (OMOE 2010), which has significant implications for the health of aquatic ecosystems through water use, urban development, and point and non-point source pollution. Several actions can assist efforts to maintain aquatic ecosystem health as the climate changes and population stressors increase:

- Continue to prevent infilling and draining activities in wetlands
- Continue to regulate surface and groundwater withdrawals to ensure wetland water budgets are maintained
- Rehabilitate wetlands through large-scale projects such as restoring riparian buffers and flow through streams buried on agricultural lands or small-scale projects such as tree planting
- Introduce or extend riparian buffers adjacent to streams to provide shading that reduces stream temperatures in response to climate-induced warming and to buffer the stream against deleterious runoff
- In regulated streams, consider converting dams and storm water ponds to bottom-draw systems so cooler waters drain into downstream reaches
- Consider limiting land-use (particularly activities that cause impervious surface cover) that can change fluvial and thermal regimes
- Limit or regulate groundwater and surface water withdrawals to maintain flow and temperatures in the streams.
- To adapting to the effects of climate change on suitable habitat for lake biota, also regulate surrounding land use, particularly discharges such as sewage effluent and phosphorus loadings that may compromise water quality
- For coldwater fish species, adjust fishing regulations such as catch limits, slot size limits, season lengths, and protected areas

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